

Ocean Thermal Energy Conversion (OTEC)

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Keywords

Ocean Temperature Differences, Ocean Thermal Energy Conversion, OTEC, Renewable Energy, Solar Energy.

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Glossary

COE	Cost of Electricity Production
CWP	Cold Water Pipe
DCC	Direct Contact Condenser
DWC	Desalinated Water Cycle
EEZ	Exclusive Economic Zone
kW	kilowatt, 10^3 watts
MSL	Mean Sea Level
MW	Megawatt, 10^6 watts
OTEC	Ocean Thermal Energy Conversion
CC-OTEC	Closed Cycle OTEC
OC-OTEC	Open Cycle OTEC
SIDS	Small Island Developing States

Summary

The vertical temperature distribution in the open ocean can be simplistically described as consisting of two layers separated by an interface. The upper layer is warmed by the sun and mixed to depths of about 100 m by wave motion. The bottom layer consists of colder water formed at high latitudes. The interface or thermocline is sometimes marked by an abrupt change in temperature but more often the change is gradual. The temperature difference between the upper (warm) and bottom (cold) layers ranges from 10 °C to 25 °C, with the higher values found in equatorial waters. To an engineer this

implies that there are two enormous reservoirs providing the heat source and the heat sink required for a heat engine. A practical application is found in a system (heat engine) designed to transform the thermal energy into electricity. This is referred to as OTEC for Ocean Thermal Energy Conversion.

Several techniques have been proposed to use this ocean thermal resource; however, at present it appears that only the closed cycle (CC-OTEC) and the open cycle (OC-OTEC) schemes have a solid foundation of theoretical as well as experimental work. In the CC-OTEC system, warm surface seawater and cold seawater are used to vaporize and condense a working fluid, such as anhydrous ammonia, which drives a turbine-generator in a closed loop producing electricity. In the OC-OTEC system seawater is flash-evaporated in a vacuum chamber. The resulting low-pressure steam is used to drive a turbine-generator. Cold seawater is used to condense the steam after it has passed through the turbine. The open-cycle can, therefore, be configured to produce desalinated water as well as electricity.

Records available from experimental plants demonstrate technical viability and provide invaluable data on the operation of OTEC plants. The economic evaluation of OTEC plants indicates that their commercial future lies in floating plants of approximately 100 MW capacity for industrialized nations and smaller plants for small-island-developing-states (SIDS). Unfortunately, the size of the experimental plants (< 0.3 MW) is about two orders of magnitude less than the size required for commercial (i.e., cost competitive) systems in industrial nations. Data extrapolation of this order is not acceptable to banking institutions or developers. The records that are available, however, are sufficient to design an OTEC plant sized at approximately 1.5 to 2 MW. This size range is appropriate for the smaller markets encountered in SIDS.

To proceed beyond experimental plants and towards commercialization in developed nations, a scaled version of a 100 MW plant must be designed and operated. The operational data is needed to earn the support required from the financial community and developers. Considering a 4-module system, a 1/5-scaled version of a 25 MW module is proposed as an appropriate size. The 5 MW pre-commercial plant is also directly applicable in some SIDS.

1) Background

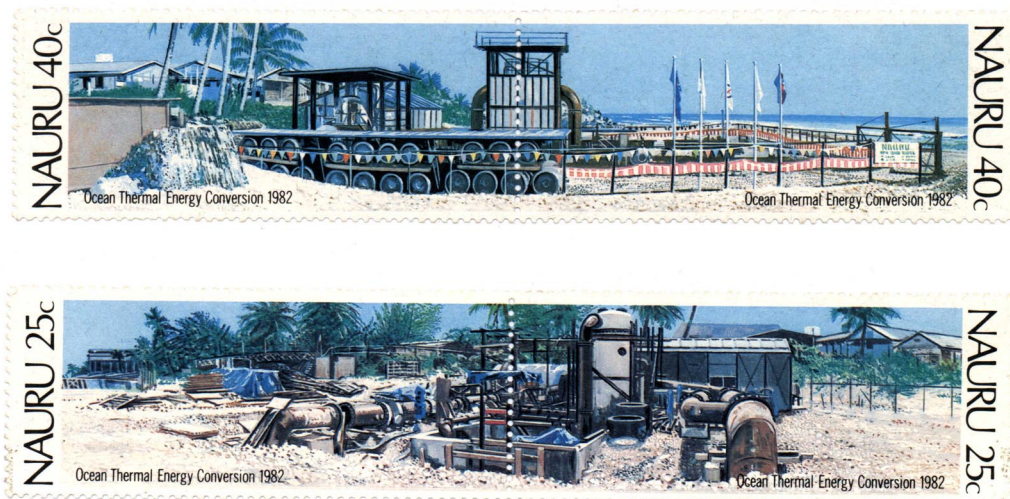
It is estimated that, in an annual basis, the amount solar energy absorbed by the oceans is equivalent to at least 4000 times the amount presently consumed by humans. For an OTEC efficiency of 3 percent, in converting ocean thermal energy to electricity, we would need less than 1 percent of this renewable energy to satisfy all of our desires for energy. However, even assuming that the removal of such relatively small amount of ocean solar energy does not pose an adverse environmental impact we must first identify and develop the means to transform it to a useful form and to transport it to the user.

The first documented reference to the use of ocean temperature differences to produce electricity is found in Jules Verne's "Twenty Thousand Leagues Under the Sea" published in 1870. Eleven years after Jules Verne, D'Arsonval proposed to use the relatively warm (24°C to 30°C) surface water of the tropical oceans to vaporize pressurized ammonia through a heat exchanger (i.e., evaporator) and use the resulting vapor to drive a turbine-generator. The cold ocean water transported (upwelled) to the surface from 800 m to 1000 m depths, with temperatures ranging from 8°C to 4°C , would condense the ammonia vapor through another heat exchanger (i.e., condenser). His concept is grounded in the thermodynamic Rankine cycle used to study steam (vapor) power plants. Because the ammonia circulates in a closed loop, this concept has been named closed-cycle OTEC (CC-OTEC).

D'Arsonval's concept was demonstrated in 1979, when a small plant mounted on a barge off Hawaii (Mini-OTEC) produced 50 kW of gross power, with a net output of 18 kW. Subsequently, a 100 kW gross power, land-based plant was operated in the island nation of Nauru by a consortium of Japanese companies. These plants were operated for a few months to demonstrate the concept. They were too small to be scaled to commercial size systems.



Mini-OTEC (1979)



Postage Stamp Issued by Nauru to Commemorate CC-OTEC Demonstration Plant (1982)

Forty years after D'Arsonval, Georges Claude, another French inventor, proposed to use the ocean water as the working fluid. In Claude's cycle the surface water is flash-evaporated in a vacuum

chamber. The resulting low-pressure steam is used to drive a turbine-generator and the relatively colder deep seawater is used to condense the steam after it has passed through the turbine. This cycle can, therefore, be configured to produce desalinated water as well as electricity. Claude's cycle is also referred to as open-cycle OTEC (OC-OTEC) because the working fluid flows once through the system. He demonstrated this cycle in 1930 in Cuba with a small land-based plant making use of a direct contact condenser (DCC). Therefore, desalinated water was not a by-product. The plant failed to achieve net power production because of a poor site selection (e.g., thermal resource) and a mismatch of the power and seawater systems. However, the plant did operate for several weeks. This was followed by the design of a 2.2 MW floating plant for the production of up to 2000 tons of ice (this was prior to the wide availability of household refrigerators) for the city of Rio de Janeiro. Claude housed his power plant in a ship (i.e., plantship), about 100 km offshore. Unfortunately, he failed in his numerous attempts to install the vertical long pipe required to transport the deep ocean water to the ship (the cold water pipe, CWP) and had to abandon his enterprise in 1935. His failure can be attributed to the absence of the offshore industry, and ocean engineering expertise presently available. His biggest technological challenge was the at-sea installation of a CWP. This situation is markedly different now that there is a proven record in the installation of several pipes during experimental operations.

The next step towards answering questions related to operation of OTEC plants was the installation of a small OC-OTEC land-based experimental facility in Hawaii. This plant was designed and operated by a team led by the author. The turbine-generator was designed for an output is 210 kW for 26 °C warm surface water and a deep water temperature 6 °C. A small fraction (10 percent) of the steam produced was diverted to a surface condenser for the production of desalinated water. The experimental plant was successfully operated for six years. The highest production rates achieved were 255 kWe (gross) with a corresponding net power of 103 kW and 0.4 l s⁻¹ of desalinated water. These are world records for OTEC.



210 kW OC-OTEC Experimental Plant (1993-1998)



Surface Condenser for Desalinated Water Production (1994-1998)

A two-stage OTEC hybrid cycle, wherein electricity is produced in a first-stage (closed cycle) followed by water production in a second-stage, has been proposed by the author and his coworkers to maximize the use of the thermal resource available to produce water and electricity. In the second-stage, the temperature difference available in the seawater effluents from an OTEC plant (e.g., 12 °C) is used to produce desalinated water through a system consisting of a flash evaporator and a surface condenser (basically, an open cycle without a turbine-generator). In the case of an open cycle plant, the addition of a second-stage results in doubling water production.

The use of the cold deep water as the chiller fluid in air conditioning (AC) systems has also been proposed. It has been determined that these systems would have tremendous economic potential as well as providing significant energy conservation independent of OTEC. For example, to produce 5800 tons (roughly equivalent to 5800 rooms) of air conditioning only 1 m³ s⁻¹ of 7 °C deep ocean water is required. The pumping power required is 360 kW as compared to 5000 kW for a conventional AC system. The investment payback period is estimated at 3 to 4 years.

A number of possible configurations for OTEC plants have been proposed. These configurations range from floating plants to land-based plants, including shelf-mounted towers and other offshore structures.

The primary candidate for commercial size plants appears to be the floating plant, positioned close to land, transmitting power to shore via a submarine power cable.

2) Technical Limitations

The performance of OTEC power generating cycles is assessed with the same elementary concepts of thermodynamics used for conventional steam power plants. The major difference arises from the large quantities of warm and cold seawater required for heat transfer processes, resulting in the consumption of 20 to 30 percent of the power generated by the turbine-generator in the operation of pumps. The power required to pump seawater is determined accounting for the pipe-fluid frictional losses and in the case of the cold seawater for the density head, i.e., gravitational energy due to the differences in density between the heavier (colder) water inside the pipe and the surrounding water column. The seawater temperature rise, due to frictional losses, is negligible for the designs presented herein.

The ideal energy conversion for 26 °C and 4 °C warm and cold seawaters is 8 percent. An actual OTEC plant will transfer heat irreversibly and produce entropy at various points in the cycle yielding an energy conversion of 3 to 4 percent. These values are small compared to efficiencies obtained for conventional power plants; however, OTEC uses a resource that is constantly renewed by the sun. Considering practical sizes for the cold water pipe OTEC is presently limited to sizes of no more than about 100 MW. In the case of the open-cycle, due to the low-pressure steam, the turbine is presently limited to sizes of no more than 2.5 MW. The thermal performance of CC-OTEC and OC-OTEC is comparable. Floating vessels approaching the dimensions of supertankers, housing factories operated with OTEC-generated electricity, or transmitting the electricity to shore via submarine power cables have been conceptualized. Large diameter pipes suspended from these plantships extending to depths of 1000 m are required to transport the deep ocean water to the heat exchangers onboard. The design and operation of these cold water pipes are major issues that have been resolved by researchers and engineers in the USA.

It has been determined that approximately $4 \text{ m}^3 \text{ s}^{-1}$ of warm seawater and $2 \text{ m}^3 \text{ s}^{-1}$ of cold seawater (ratio of 2:1), with a nominal temperature difference of 20 °C, are required per MW of exportable or net electricity (net = gross - inhouse usage). To keep the water pumping losses at about 20 to 30 percent of the gross power, an average speed of less than 2 m s^{-1} is considered for the seawater flowing through the pipes transporting the seawater resource to the OTEC power block. Therefore, a 100 MW plant would use $400 \text{ m}^3 \text{ s}^{-1}$ of 26 °C water flowing through a 16 m inside diameter pipe extending to a depth of 20 m; and $200 \text{ m}^3 \text{ s}^{-1}$ of 4 °C water flowing through an 11 m diameter pipe extending to depths of 1000 m. Using similar arguments, a 20 m diameter pipe is required for the mixed water return. To minimize the environmental impact due to the return of the processed water to the ocean (mostly changes in temperature), a discharge depth of 60 m is sufficient for most sites considered feasible, resulting in a pipe extending to depths of 60 m.

The amount of total world power that could be provided by OTEC must be balanced with the impact to the marine environment that might be caused by the relatively massive amounts of seawater required to operate OTEC plants. The discharge water from a 100 MW plant would be equivalent to the nominal flow of the Colorado River into the Pacific Ocean (1/10 the Danube, or 1/30 the Mississippi, or 1/5 the Nile into the Atlantic). The discharge flow from 60,000 MW (0.6 percent of present world consumption) of OTEC plants would be equivalent to the combined discharge from all rivers flowing into the Atlantic and Pacific Oceans ($361,000 \text{ m}^3 \text{ s}^{-1}$). Although river runoff composition is

considerably different from the OTEC discharge, providing a significant amount of power to the world with OTEC might have an impact on the environment below the oceanic mixed layer and, therefore, could have long-term significance in the marine environment. However, numerous countries throughout the world could use OTEC as a component of their energy equation with relatively minimal environmental impact. Tropical and subtropical island sites could be made independent of conventional fuels for the production of electricity and desalinated water by using plants of appropriate size. The larger question of OTEC as a significant provider of power for the world cannot be assessed, beyond the experimental plant stage, until some operational and environmental impact data is made available through the construction and operation of the pre-commercial plant mentioned above.

3) OTEC and the Environment

OTEC offers one of the most benign power production technologies, since the handling of hazardous substances is limited to the working fluid (e.g., ammonia), and no noxious by-products are generated. OTEC requires drawing seawater from the mixed layer and the deep ocean and returning it to the mixed layer, close to the thermocline, which could be accomplished with minimal environmental impact. The carbon dioxide out-gassing from the seawater used for the operation of an OC-OTEC plant is less than 1 percent of the approximately 700 grams per kWh amount released by fuel oil plants. The value is even lower in the case of a CC-OTEC plant.

A sustained flow of cold, nutrient-rich, bacteria-free deep ocean water could cause sea surface temperature anomalies and biostimulation if resident times in the mixed layer and the euphotic zone respectively are long enough (i.e., upwelling). The euphotic zone is the upper layer of the ocean in which there is sufficient light for photosynthesis. This has been taken to mean the 1 percent-light-penetration depth (e.g., 120 m in Hawaiian waters). This is unduly conservative, because most biological activity requires radiation levels of at least 10 percent of the sea surface value. Since light intensity decreases exponentially with depth, the critical 10 percent-light-penetration depth corresponds to, for example, 60 m in Hawaiian waters. The analyses of specific OTEC designs indicate that mixed seawater returned at depths of 60 m results in a dilution coefficient of 4 (i.e., 1 part OTEC effluent is mixed with 3 parts of the ambient seawater) and equilibrium (neutral buoyancy) depths below the mixed layer throughout the year. This water return depth also provides the vertical separation, from the warm water intake at about 20 m, required to avoid reingestion into the plant. This value will vary as a function of ocean current conditions. It follows that the marine food web should be minimally affected and that persistent sea surface temperature anomalies should not be induced. These conclusions need to be confirmed with actual field measurements that could be performed with the pre-commercial plant described in Section 9.

To have effective heat transfer it is necessary to protect the heat exchangers from biofouling. It has been determined that biofouling only occurs in OTEC heat exchangers exposed to surface seawater. Therefore, it is only necessary to protect the CC-OTEC evaporators. Chlorine (Cl_2) has been proposed along with several mechanical means. Depending upon the type of evaporator, both chemical and mechanical means could be used. To protect marine life, the Environmental Protection Agency (EPA) in the USA allows a maximum Cl_2 discharge of 0.5 mg l^{-1} and an average of 0.1 mg l^{-1} . CC-OTEC plants need to use Cl_2 at levels of less than 10 percent of the EPA limits. The power plant components will release small quantities of working fluid during operations. Marine discharges will depend on the working fluid, the biocides, the depth of intake and the discharge configuration chosen.

Other potentially significant concerns are related to the construction phase. These are similar to those associated with the construction of any power plant, shipbuilding and the construction of offshore platforms. What is unique to OTEC is the movement of seawater streams with flow rates comparable to those of rivers and the effect of passing such streams through the OTEC components before returning them to the ocean. The use of biocides and ammonia are similar to other human activities. If occupational health and safety regulations like those in effect in the USA are followed, working fluid and biocide (most probably anhydrous ammonia and chlorine) emissions from a plant should be too low to detect outside the plant sites. A major release of working fluid or biocide would be hazardous to plant workers, and potentially hazardous to the populace in surrounding areas, depending on their proximity. Both ammonia and chlorine can damage the eyes, skin, and mucous membranes, and can inhibit respiration. Should an accident occur with either system, the risks are similar to those for other industrial applications involving these chemicals. Ammonia is used as a fertilizer and in ice skating rink refrigeration systems. Chlorine is used in municipal water treatment plants and in steam power plants. Chlorine can be generated *in situ*; therefore storage of large quantities of chlorine is not recommended.

Organisms impinged by an OTEC plant are caught on the screens protecting the intakes. Impingement is fatal to the organism. An entrained organism is drawn into and passes through the plant. Entrained organisms may be exposed to biocides, and temperature and pressure shock. Entrained organisms may also be exposed to working fluid and trace constituents (trace metals and oil or grease). Intakes should be designed to limit the inlet flow velocity to minimize entrainment and impingement. The inlets need to be tailored hydrodynamically so that withdrawal does not result in turbulence or recirculation zones in the immediate vicinity of the plant. Many, if not all, organisms impinged or entrained by the intake waters may be damaged or killed. Although experiments suggest that mortality rates for phytoplankton and zooplankton entrained by the warm-water intake may be less than 100 percent, in fact only a fraction of the phytoplankton crops from the surface may be killed by entrainment. Prudence suggests that for the purpose of assessment, 100 percent capture and 100 percent mortality upon capture should be assumed unless further evidence exists to the contrary. Metallic structural elements (e.g., heat exchangers, pump impellers, metallic piping) corroded or eroded by seawater will add trace elements to the effluent. It is difficult to predict whether metals released from a plant will affect local biota. Trace elements differ in their toxicity and resistance to corrosion. Few studies have been conducted of tropical and subtropical species. Furthermore, trace metals released by OTEC plants will be quickly diluted with great volumes of water passing through the plant. However, the sheer size of an OTEC plant circulation system suggests that the aggregate of trace constituents released from the plant or redistributed from natural sources could have long-term significance for some organisms.

OTEC plant construction and operation may affect commercial and recreational fishing. Fish will be attracted to the plant, potentially increasing fishing in the area. Enhanced productivity due to redistribution of nutrients may improve fishing. However, the losses of inshore fish eggs and larvae, as well as juvenile fish, due to impingement and entrainment and to the discharge of biocides may reduce fish populations. The net effect of OTEC operation on aquatic life will depend on the balance achieved between these two effects. Through adequate planning and coordination with the local community, recreational assets near an OTEC site may be enhanced.

Other risks associated with the OTEC power system are the safety issues associated with steam electric power generation plants: electrical hazards, rotating machinery, use of compressed gases, heavy material-handling equipment, and shop and maintenance hazards. Because the CC-OTEC power plant

operates as a low-temperature, low pressure Rankine cycle, it poses less hazard to operating personnel and the local population than conventional fossil-fuel plants. It is essential that all potentially significant concerns be examined and assessed for each site and design to assure that OTEC is an environmentally benign and safe alternative to conventional power generation. The consensus among researchers is that the potentially detrimental effects of OTEC plants on the environment can be avoided or mitigated by proper design.

4) Engineering Challenges

The design and installation of a cost-effective pipe to transport large quantities of cold water to the surface (i.e., cold water pipe, CWP) presented an engineering challenge of significant magnitude complicated by a lack of evolutionary experience. This challenge was met in the USA with a program relying on computer-aided analytical studies integrated with laboratory and at-sea tests. The greatest outcome achieved has been the design, fabrication, transportation, deployment and test at-sea of an instrumented 2.4 m diameter, 120 m long, fiberglass reinforced plastic (FRP) sandwich construction pipe attached to a barge. The data obtained was used to validate the design technology developed for pipes suspended from floating OTEC plants. This type of pipe is recommended for floating OTEC plants. For land-based plants there is a validated design for high-density polyethylene pipes of diameter less than 1.6 m. In the case of larger diameter pipes offshore techniques used to deploy large segmented pipes made of steel, concrete or FRP are applicable. Pressurized pipes made of reinforced elastomeric fabrics (e.g., soft pipes), with pumps located at the cold water intake, seem to offer the most innovative alternative to conventional concepts. However, the operability of pumps in 800 m to 1000 m water depths over extended periods must be verified and the inspection, maintenance and repair (IM&R) constraints established before soft pipes can be used in practical designs.

Other components for OTEC floating plants that present engineering challenges are the position keeping system and the attachment of the submarine power cable to the floating plant. Deep ocean-mooring systems, designed for water depths of more than 1000 m, or dynamic positioning thrusters developed by the offshore industry can be used for position keeping. The warm water intake and the mixed return water also provide the momentum necessary to position the surface vessel. The offshore industry also provides the engineering and technological backgrounds required to design and install the riser for the submarine power cable.

The design of OTEC CWPs, mooring systems and the submarine power cable must take into consideration survivability loads as well as fatigue induced loads. The first kind is based on extreme environmental phenomena, with a relatively long return period, that might result in ultimate strength failure while the second kind might result in fatigue-induced failure through normal operations.

5) Open Cycle OTEC

The open cycle consists of the following steps: (i) flash evaporation of a fraction of the warm seawater by reduction of pressure below the saturation value corresponding to its temperature (ii) expansion of the vapor through a turbine to generate power; (iii) heat transfer to the cold seawater thermal sink resulting in condensation of the working fluid; and (iv) compression of the non-condensable gases (air released from the seawater streams at the low operating pressure) to pressures required to discharge them from the system. These steps are depicted in Figure 1. In the case of a surface condenser the condensate (desalinated water) must be compressed to pressures required to discharge it from the power generating system.

The evaporator, turbine, and condenser operate in partial vacuum ranging from 3 percent to 1 percent atmospheric pressure. This poses a number of practical concerns that must be addressed. First, the system must be carefully sealed to prevent in-leakage of atmospheric air that can severely degrade or shut down operation. Second, the specific volume of the low-pressure steam is very large compared to that of the pressurized working fluid used in closed cycle OTEC. This means that components must have large flow areas to ensure that steam velocities do not attain excessively high values. Finally, gases such as oxygen, nitrogen and carbon dioxide that are dissolved in seawater (essentially air) come out of solution in a vacuum. These gases are uncondensable and must be exhausted from the system. In spite of the aforementioned complications, the Claude cycle enjoys certain benefits from the selection of water as the working fluid. Water, unlike ammonia, is non-toxic and environmentally benign. Moreover, since the evaporator produces desalinated steam, the condenser can be designed to yield fresh water. In many potential sites in the tropics, potable water is a highly desired commodity that can be marketed to offset the price of OTEC-generated electricity.

Flash evaporation is a distinguishing feature of open cycle OTEC. Flash evaporation involves complex heat and mass transfer processes. In the configuration tested by a team lead by the author, warm seawater was pumped into a chamber through spouts designed to maximize the heat-and-mass-transfer surface area by producing a spray of the liquid. The pressure in the chamber (2.6 percent of atmospheric) was less than the saturation pressure of the warm seawater. Exposed to this low-pressure environment, water in the spray began to boil. As in thermal desalination plants, the vapor produced was relatively pure steam. As steam is generated, it carries away with it its heat of vaporization. This energy comes from the liquid phase and results in a lowering of the liquid temperature and the cessation of boiling. Thus, as mentioned above, flash evaporation may be seen as a transfer of thermal energy from the bulk of the warm seawater to the small fraction of mass that is vaporized to become the working fluid. Approximately 0.5 percent of the mass of warm seawater entering the evaporator is converted into steam.

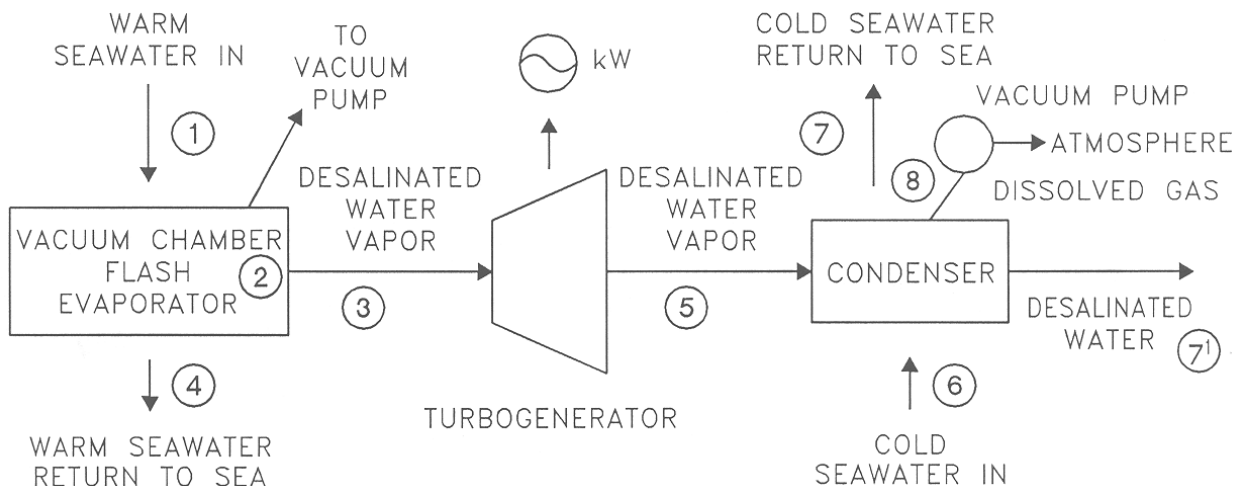


Figure 1. Open-Cycle OTEC Flow Diagram.

A large turbine is required to accommodate the huge volumetric flow rates of low-pressure steam needed to generate any practical amount of electrical power. Although the last stages of turbines used in conventional steam power plants can be adapted to OC- OTEC operating conditions, existing technology limits the power that can be generated by a single turbine module, comprising a pair of rotors, to about 2.5 MW. Unless significant effort is invested to develop new, specialized turbines (which may employ fiber-reinforced plastic blades in rotors having diameters in excess of 100 m), increasing the gross power generating capacity of a Claude cycle plant above 2.5 MW will require multiple modules and incur an associated equipment cost penalty. Condensation of the low-pressure working fluid leaving the turbine occurs by heat transfer to the cold seawater. This heat transfer may occur in a DCC, in which the seawater is sprayed directly over the vapor, or in a surface condenser that does not allow contact between the coolant and the condensate. DCCs are relatively inexpensive and have good heat transfer characteristics due to the lack of a solid thermal boundary between the warm and cool fluids. Although surface condensers for OTEC applications are relatively expensive to fabricate they permit the production of desalinated water. Desalinated water production with a DCC requires the use of fresh water as the coolant. In such an arrangement, the cold seawater sink is used to chill the fresh water coolant supply using a liquid-to-liquid heat exchanger.

Effluent from the low-pressure condenser must be returned to the environment. Liquid can be pressurized to ambient conditions at the point of discharge by means of a pump or, if the elevation of the condenser is suitably high, it can be compressed hydrostatically. Non-condensable gases, which include any residual water vapor, dissolved gases that have come out of solution, and air that may have leaked into the system, must be pressurized with a compressor. Although the primary role of the compressor is to discharge exhaust gases, it usually is perceived as the means to reduce pressure in the system below atmospheric. For a system that includes both the OC-OTEC heat engine and its environment, the cycle is closed and parallels the Rankine cycle. Here, the condensate discharge pump and the non-condensable gas compressor assume the role of the Rankine cycle pump.

The analysis of the cycle yields (Figure 1):

$$\text{Heat (added) absorbed from seawater (J/s)} \quad q_w = \dot{m}_{ww} C_p (T_{wwi} - T_{wwo})$$

$$\text{Steam generation rate (kg/s)} \quad \dot{m}_s = q_w / h_{fg}$$

$$\text{Turbine work (J/s)} \quad w_T = \dot{m}_s (h_3 - h_5) = \dot{m}_s \eta_T (h_3 - h_{5s})$$

$$\text{Heat (rejected) into seawater (J/s)} \quad q_c = \dot{m}_{cw} C_p (T_{cwo} - T_{cwi})$$

where,

\dot{m}_{ww} is the mass flow rate of warm water; C_p the specific heat; T_{wwi} and T_{wwo} the seawater temperature at the inlet and outlet of the heat exchanger; h_{fg} the heat of evaporation; and the enthalpies at the indicated points are given by h , with the subscript s referring to constant entropy. The turbine isentropic efficiency is given by η_T . The subscript cw refers to the cold water.

6) The 210 kW OC-OTEC Experimental Apparatus

As stated above, a 210 kW OC-OTEC Experimental Apparatus was conceived as the next step towards answering questions related to operation of OTEC plants. The apparatus was operated for six years (1993-1998) providing valuable data and pointing the way for future modifications and improvements in the OC-OTEC process. The turbine-generator was designed for an output is 210 kW for 26 °C warm surface water and a deep water temperature 6 °C. A small fraction (10 percent) of the steam produced was diverted to a surface condenser for the production of desalinated water. The highest production rates achieved were 255 kW (gross) with a corresponding net power of 103 kW and 0.4 l s^{-1} of desalinated water. These are world records for OTEC. It must be noted that the net power was not optimized because pumping losses were relatively high due to the use of a seawater system that was already available. It is expected that for a commercial size plant the ratio of net to gross power will be approximately 0.7.

The data and experience obtained demonstrated that the OC-OTEC process is technically feasible for the production of base load electricity and desalinated water. It was also demonstrated that frequency control in the island mode is achieved with either a load-diversion-governor (LDG) or with the vacuum compression system. The most significant and exciting lessons learned were those that were fundamental new insights into the OC-OTEC process. The two main discoveries were the unstable synchronous generator output, and the violent outgassing of seawater in the heat exchangers. The most annoying problem was the frequent failures of the grease lubricated bearings of the centrifugal pumps used for the vacuum and exhaust system. In retrospect, this was due to a major design oversight. Equipment operating at speeds higher than approximately 27,000 revolutions-per-minute should, in general, not use grease lubricated bearings. It was concluded that high speed centrifugal pumps with, for example, magnetic bearings can be used in future OC-OTEC systems to achieve extended life cycles, relatively low power consumption and, therefore, optimum net power.

7) Design of a Small Land-Based OC-OTEC Plant

To understand the details of the design and operation of a Claude Cycle plant, it is useful to consider a specific example given by the design of a small land-based plant. The design philosophy reflects an emphasis on feasibility: a state-of-the-art cold water supply pipeline, a 1.6 m high-density-polyethylene (HDPE) conduit, was selected as the design starting point, rather than a prescribed net power output. Consistent with this choice, some critical hardware components were preferred over alternative configurations because they are presently available off-the-shelf. The major conclusion is that cost-effective electricity and desalinated water could be supplied to small South Pacific Island communities if appropriate financing is available. Depending on the importance of desalinated water for these communities, two global design options were identified:

- 1) OC-OTEC power plant proper, with a net power production capability of about 1.2 MW and desalinated water production of 2200 m^3 per day;
 - 2) OC-OTEC power plant fitted with a second-stage water flashing unit, with a net power production capability of about 1.1 MW and desalinated water production of 5150 m^3 per day.
- In addition, a 300-room air conditioning system can be included for resort development.

These configurations are cost competitive with conventional power plants if investment loans with interest rates of less than 5 percent are available and if credit for desalinated water and air-conditioning byproducts are included. However, the transfer of OTEC to small Pacific Islands should not be exclusively assessed from the perspective of present-day cost effectiveness since it offers these isolated

communities some degree of energy independence while preserving their environment. In this regard the most important finding is not related to technical matters but rather to financial considerations: the announcement by industrialized countries, after the Kyoto Conference, that low interest loans would be made available to developing countries for renewable energy projects with minimal environmental impact.

The heat and mass balance is given in Figure 2. A 6156 kg s^{-1} flow rate of warm seawater at 26°C is supplied via a 2.5 m ID FRP pipe. The pipe has an intake depth of 25 m and is 120 m long. Five inline dry motor vertical turbine propeller pumps (three operational, two standby) supply the flow to an intake pool below the first stage evaporator. The intake pool has a nominal operating level of 2.78 m from mean sea level (MSL). This level is selected to provide enough head (level) in the mixed flow discharge pool for gravity discharge into the ocean. Three inline submersible propeller-type pumps (two operational, one standby) bring 3175 kg s^{-1} of cold seawater through a 1.6 m OD pipe from a depth of 1000 m. The pipe length is 2590 m. A 3085 kg s^{-1} flow rate of 4°C cold seawater is available for the OTEC system, whereas 90 kg s^{-1} is reserved for air-conditioning applications. An upriser takes the warm water into the evaporator. A pre-deaeration nozzle removes a portion of the non-condensables from the warm water accumulated below the spout plate. The evaporator spout plate has 122 spouts and the warm water flashes through the spouts into the evaporation chamber at a pressure of 2.76 kPa. A small fraction (26.1 kg s^{-1}) of supply water is changed into steam and the rest is discharged into the first stage discharge pool at a temperature of 23.4°C . The discharge pool at a level of 1.76 m MSL also acts as the supply pool for the second stage evaporator. The evaporation pressure in the second stage is 2.22 kPa. No pre-deaeration is provided in the second stage as the water has been deaerated in the first stage. The steam flow from the second stage evaporator is 34 kg s^{-1} . The effluent water from the second stage evaporator at 20°C goes into the mixed water discharge pool.

Steam from the first stage evaporator enters the turbine at 2.74 kPa and leaves the turbine diffuser system at 1.29 kPa. The turbine generator system gives a gross output of 1838 kW. Steam exhausted from the turbine-diffuser system enters the first stage main surface condenser. The main condenser receives 2702 kg s^{-1} of cold seawater at 4°C and condenses 92 percent of the incoming steam. The vent condenser gets 281 kg s^{-1} of 4°C cold seawater supply and condenses 90 percent of the steam leaving the main condenser. The remaining steam and the non-condensables are evacuated by the vacuum compressor system. Steam generated by the second stage evaporator enters the second stage main condenser at 2.18 kPa and 19.2°C . This steam is expected to be virtually free of non-condensables. The condenser receives 3085 kg s^{-1} of cold seawater at 9.4°C and discharges it at 16.2°C . The minimal amount of uncondensed steam, along with any non-condensables, goes to a vent condenser. A hook-up is provided to let the vapor compressor system remove any non-condensables and water vapor from the vent condenser.

Non-condensables and steam vapor from the first and second stage vent condenser enters the vacuum compressor system through a counter-current direct contact pre-cooler. The pre-cooler receives 4°C cold seawater and ensures that the mixture temperature at the first stage inlet of the compressor system is not more than 5°C and that the entire vapor is condensed until its partial pressure becomes equal to the seawater saturation pressure at 5°C . The basic compressor system has four stages with direct contact coolers in-between. The fourth stage compressor takes the non-condensables from the third stage. The discharge from the fourth stage is re-injected at 30 kPa into the warm water effluent

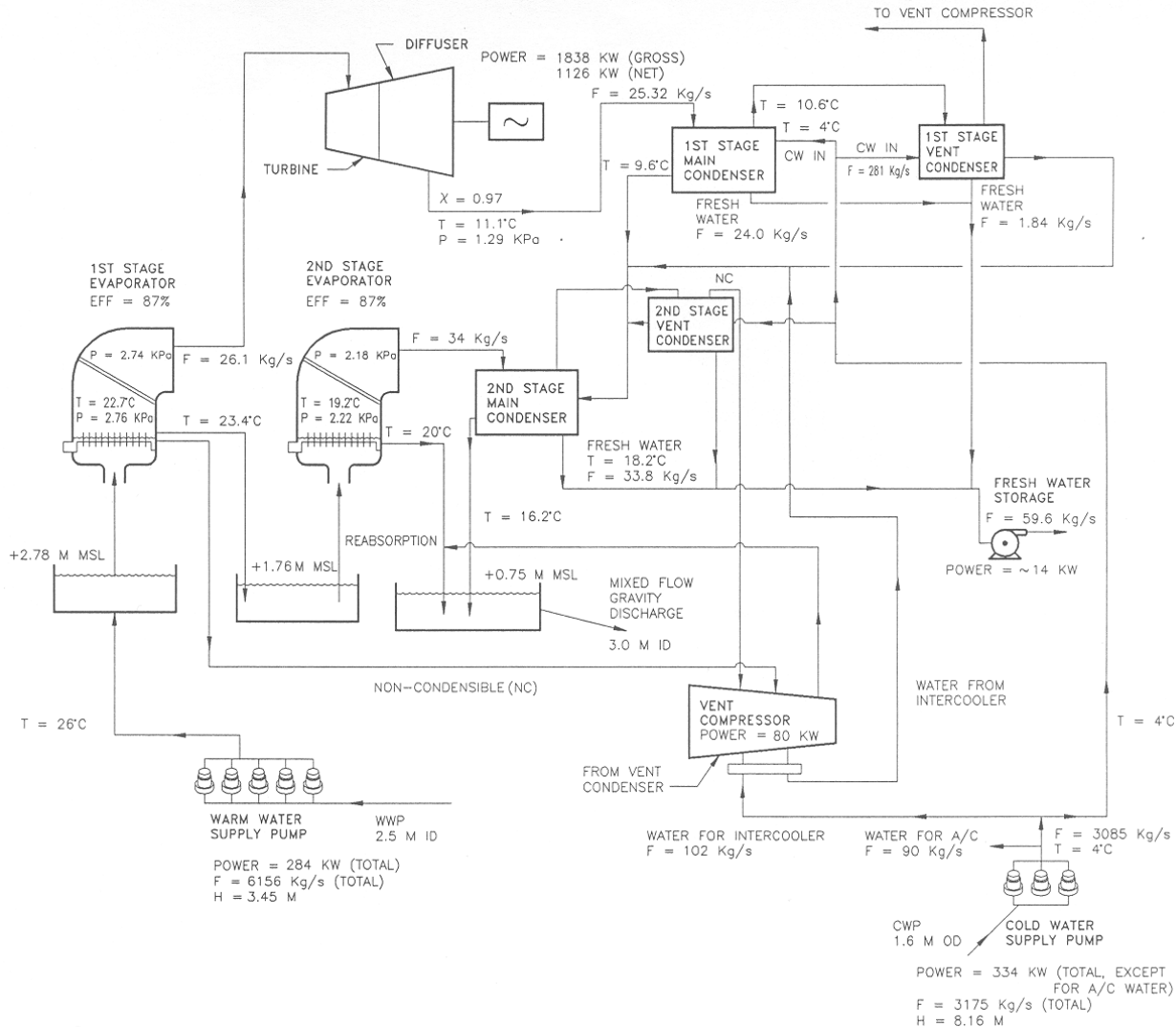


Figure 2. Heat and Mass Balance of a 1.8 MW-gross OC-OTEC Plant with Additional 2nd Stage Seawater Desalination.

returning from the second stage evaporator. A fifth stage compressor is also provided to alternately bypass the re-injection scheme and discharge into the atmosphere. The first four stages are centrifugal, whereas the fifth stage is a positive displacement type.

The cold and warm water effluents from the second stage combine into a mixed discharge pool with a nominal level of 0.75m MSL. A 3 m ID, 190 m long and 60 m deep pipe provides gravity discharge recourse for the mixed water system. The net power from the system is 1126 kW obtained after subtracting 334 kW for cold water supply pumping; 284 kW for warm water supply pumping; 80 kW for compressor system; and 14 kW for desalinated water pumping from the gross power produced. Without second stage water production the combined pumping losses will be reduced by approximately 100 kW (net increase) and the desalinated water production would be 25.8 kg s^{-1} .

8) Closed Cycle OTEC

The operation of a closed-cycle OTEC plant, using anhydrous ammonia as the working fluid, is modeled with the saturated Rankine cycle. Figure 3 shows a simplified flow diagram of the CC-OTEC cycle. The analysis of the cycle is straightforward. Based on a unit mass flow rate of ammonia vapor (kg s^{-1}) in the saturated cycle:

Heat added (J / kg) $q_A = h_1 - h_4$

Turbine work (J / kg) $w_T = h_1 - h_2$

Heat Rejected (J / kg) $|q_R| = h_2 - h_3$

Pump work (J / kg) $|w_p| = h_4 - h_3$

Cycle net work (J / kg) $\Delta w_{\text{net}} = (h_1 - h_2) - (h_4 - h_3)$

Thermal efficiency $\eta_{\text{th}} = \frac{w_{\text{net}}}{q_A} = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_4)}$

where, h is the enthalpy at the indicated state point. It follows that the heat-added plus the pump-work is equal to the heat-rejected plus the turbine-work.

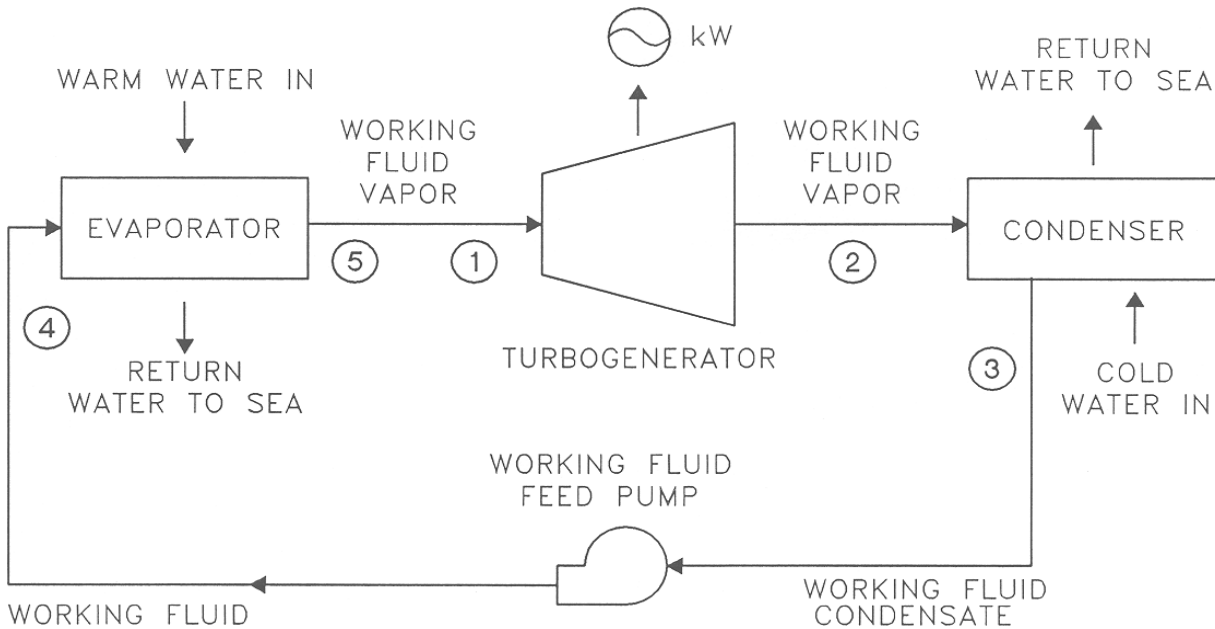


Figure 3. Closed-Cycle OTEC Flow Diagram.

9) Design of a Pre-Commercial Floating Hybrid-OTEC Plant

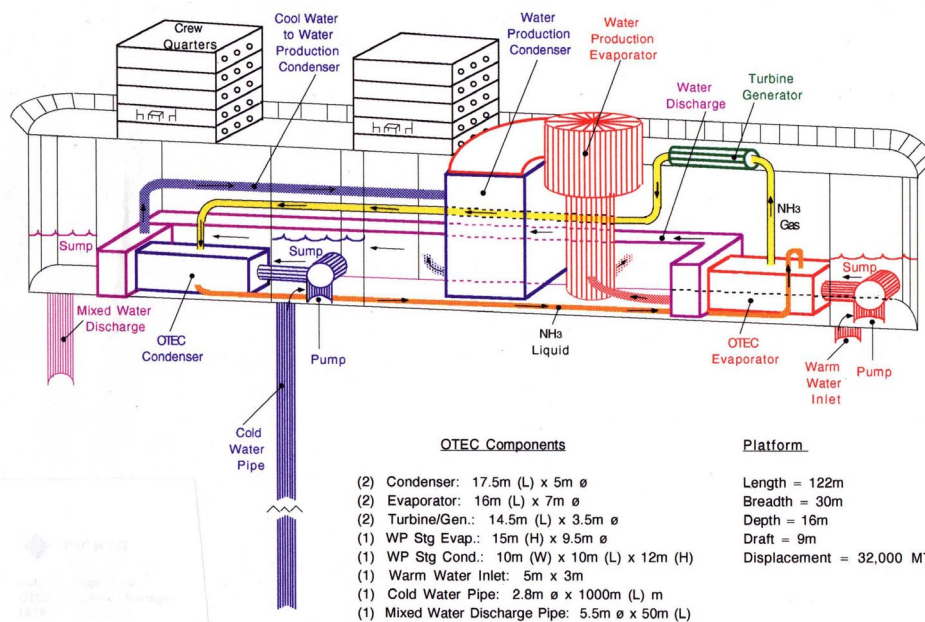
To understand the details of the design and operation of a CC-OTEC plant, it is useful to consider a specific example given by the 5 MW (nominal) floating hybrid-OTEC. The author conceived this plant, as the pre-commercial plant needed to demonstrate the technical and economical viability of OTEC and to assess the environmental impact. Unfortunately, funding was not secured.

A simplified flow diagram of the power cycle is shown in Figure 4. The plant is based on a closed-cycle for electricity production and on a second stage, using the effluent water streams from the power cycle, for desalinated water production. The baseline is for a floating plant, i.e., the power and water cycles are housed in a barge or ship with the electricity transmitted to shore via a 15 cm submarine power cable and the desalinated water via a small, 15 to 16 cm diameter hose pipe.

Assuming temperatures of 26 °C and 4.5 °C for the surface and deep ocean waters, in the electricity production mode, a gross power output of 7920 kW, using off-the-shelf technology, is sufficient to produce 5260 kW-net with an in-plant consumption of 2660 kW. The power output for this cycle varies as a function of surface water temperature (the cold water temperature is essentially constant) by 860 kW per °C. For example, for 28 °C temperature (average summer conditions in Hawaii) the output would be 6980 kW-net. With the combined production of desalinated water and electricity, the baseline outputs would be 5100 kW-net (160 kW required for the second stage plant) and a daily production of 2281 m³ of desalinated water. This water output is only 20 percent of the amount that can be produced with the second stage.

The proposed baseline facility will employ pressurized ammonia as the working fluid in the power cycle. The baseline seawater flow rates are: 26.4 m³ per day of warm water and 13.9 m³ per day of cold water. These flow rates can be supplied using validated technologies. A 2.74 m (inside diameter) glass fiber reinforced plastic (FRP) cold water pipe will be suspended from the barge to a depth of 1000 m.

5 MWe OTEC Pre-Commercial Plant



Warm seawater will be drawn in through a 4.6 m FRP pipe from a depth of 20 m. The mixed effluent will be discharged through a 5.5 m FRP pipe at a depth of 60 m. This discharge depth has been selected to minimize the environmental impact. The baseline design employs compact heat exchangers for the evaporator and condenser. A chlorinating unit will be installed to minimize biofouling of the evaporator passages. It is known that biofouling from cold seawater is negligible and that evaporator fouling can be controlled effectively by intermittent chlorinating (50-100 parts per billion chlorine for 1 hour every day). Monitoring of the effluent water for elevated concentrations of ammonia or chlorine will be performed on a regular basis.

The seawater effluents from the power cycle exhibit a temperature difference of 12 °C. This residual thermal gradient could not be used in an additional power stage, but it allows the production of significant amounts of desalinated water through a Desalinated Water Cycle (DWC)

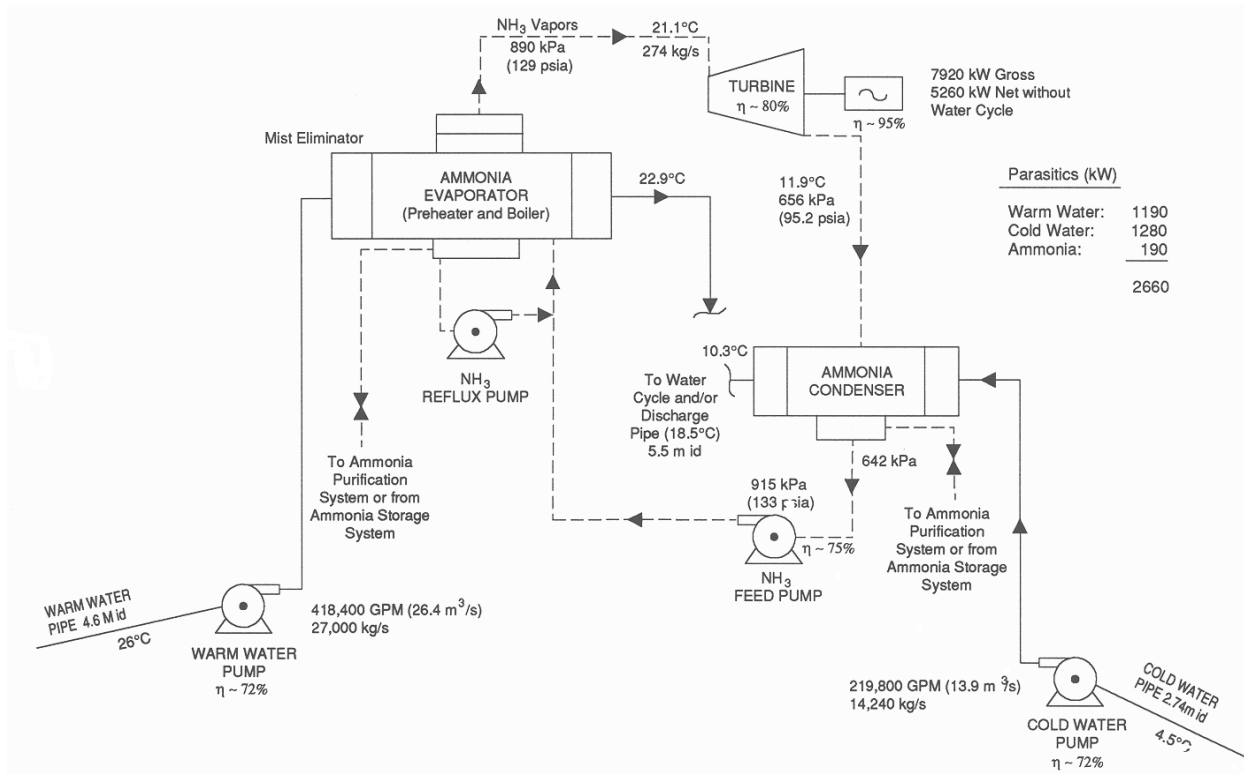


Figure 4. Heat and Mass Balance of a Pre-Commercial Hybrid OTEC Plant.

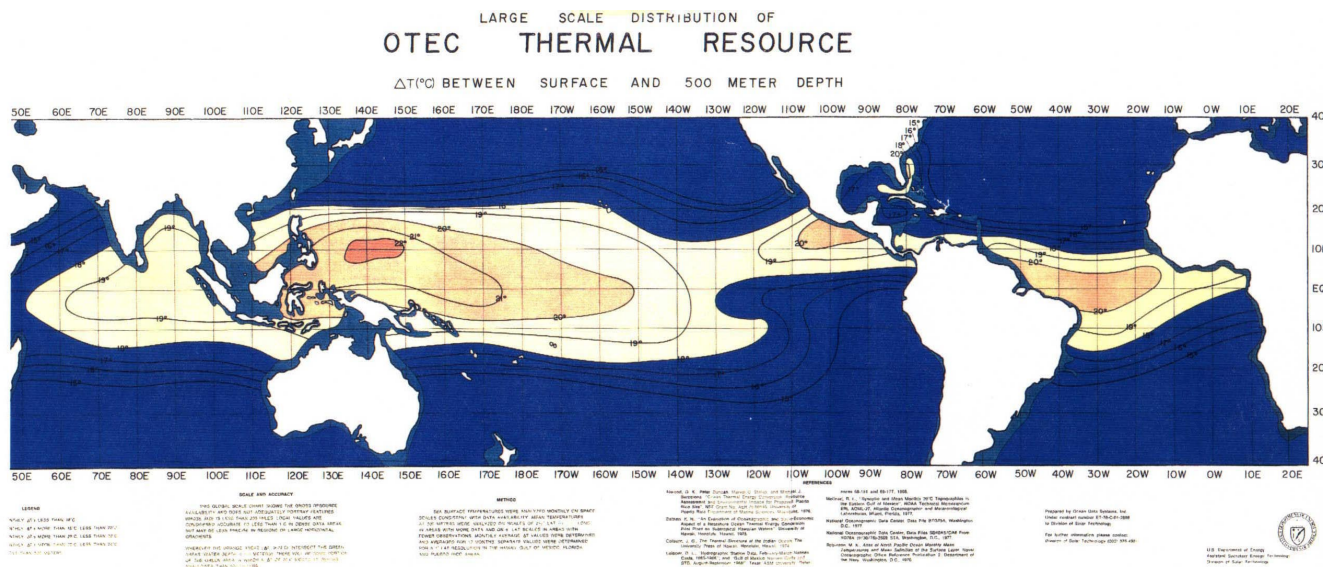
or second stage water production. The DWC is an OC-OTEC cycle without the turbine. In a low-pressure vessel, or evaporator, the warm seawater is partially flashed into steam. The evaporator is connected to two surface condensers, where the steam is converted into desalinated (fresh) water by exchanging heat with the cold seawater. During this process, dissolved gases, mainly nitrogen and oxygen, are released from the warm seawater when pressures as low as 2 percent of an atmosphere are reached. These non-condensable gases must be evacuated continuously from the second condenser, or vent condenser, by a vacuum compressor to prevent accumulation and sustain the required low operating pressures. Non-condensables also adversely affect condensation performance through a

blanketing effect at the heat exchanger walls. To reduce the impact of released non-condensable gases, a pre-deaeration chamber at about 17 kPa is installed below the flashing chamber, so that much outgassing occurs before steam generation, and at a higher pressure more suitable for compression. Moreover, gases are discharged into the warm seawater effluent at subatmospheric pressures of about 30 kPa, a procedure that not only saves power, but also restores the gas content of the warm seawater before it returns to the ocean.

10) Potential Sites

The following summarizes the availability of the OTEC thermal resource throughout the world:

(1) Equatorial waters, defined as lying between 10 °N and 10 °S are adequate except for the West Coast of South America; significant seasonal temperature enhancement (e.g., with solar ponds) would be required on the West Coast of Southern Africa; moreover, deep water temperature is warmer by about 2 °C along the East Coast of Africa. (2) Tropical waters, defined as extending from the equatorial region boundary to, respectively, 20 °N and 20 °S, are adequate, except for the West Coasts of South America and of Southern Africa; moreover, seasonal upwelling phenomena would require significant temperature enhancement for the West Coast of Northern Africa, the Horn of Africa, and off the Arabian Peninsula. The physical factors affecting OTEC site selection, i.e., thermal resource and seafloor bathymetry, greatly restrict the number of desirable sites along the shoreline of major continents, unless some warm seawater temperature enhancement is possible. The best, land-based, OTEC sites consist of island locations. The severe constraint of a favorable bathymetric profile, for the practical implementation of land-based OTEC technologies, would be relaxed to a considerable extent with floating OTEC plants. The potential benefits of OTEC could only be recovered on a large scale through the development of an ambitious floating-plant program, following the initial experimental land-based OTEC phase.



installation phases. If an island is under development, it is likely to lack the infrastructure desirable for this type of project, including harbors, airports, good roads and communication systems. Moreover, the population base should be compatible with the OTEC plant size – adequate personnel must be supplied to operate the plant, and the electricity and desalinated water plant outputs should match local consumption in orders of magnitude. 1 to 10 MW plants would generally suffice in most small Pacific islands, whereas in the case of populous and industrialized countries several of the largest feasible OTEC plants, up to 100 MW, could be considered.

There are at least two distinct markets for OTEC: (i) industrialized nations and islands; and, (ii) smaller or less industrialized islands with modest needs for power and desalinated water. Small OC-OTEC plants can be sized to produce from 1 MW to 10 MW of electricity, and at least 1700 m³ to 3500 m³ of desalinated water per day. That is, the needs of developing communities with populations ranging from 4500 to as much as 100,000 could be met. This range encompasses the majority of less developed island nations throughout the world. Larger CC-OTEC or hybrid cycle plants can be used in either market for producing electricity and water. For example, a 50 MW hybrid cycle plant producing as much as 62,000 m³ of water per day could be tailored to support a developing community of approximately 300,000 people or as many as 100,000 people in an industrialized nation.

A study performed for the US Department of State in 1981, identified ninety-eight nations and territories with access to the OTEC thermal resource (20 °C temperature difference between surface water and deep ocean water) within their 200 nautical miles EEZ, exclusive economic zone. For the majority of these locations, the OTEC resource is applicable only to floating plants. A significant market potential of up to 577,000 MW of new baseload electric power facilities was postulated (equivalent to 6 percent of present day power consumption by humanity). In view of the discussion given above, this volume of power production will represent an environmental impact of significant proportion, primarily due to the movement of massive amounts of seawater. Unfortunately, now as in 1981, there is no commercial size OTEC plant with an operational record available. This still remains an impediment to OTEC development.

11) Economic Considerations and Market Potential

In considering the economics of OTEC, it is appropriate to determine if multiple-product systems, e.g., electricity, desalinated water, mariculture, and air conditioning (AC) systems yield higher value by, for example, decreasing the equivalent cost of electricity. Because mariculture operations, as in the case of AC systems, can only use a relatively minute amount of the seawater required for the thermal plants they should be evaluated independent of OTEC. For example, the cold water available from a 1 MW OTEC plant could be used for daily exchanges of twenty-five 100 m x 100 m x 1 m mariculture ponds, requiring more than 25 Ha of land. Therefore, it is recommended that OTEC be considered for its potential impact in the production of electricity and desalinated water and that mariculture and AC systems, based in the use of deep ocean water, be considered decoupled from OTEC.

OTEC is capital-intensive (see Figure 5), and the very first plants will most probably be small requiring a substantial capital investment. Given the relatively low cost of crude oil, and of fossil fuels in general, the development of OTEC technologies is likely to be promoted by government agencies rather than by private industry. The motivation of governments in subsidizing OTEC may vary greatly, from foreign aid to domestic concerns. For the former case, ideal recipient countries are likely to be independent developing nations. If their economic standing is too low, however, the installation of an

OTEC plant, rather than direct aid in the form of money and goods, may be perceived as inadequate help. In addition, political instability could jeopardize the good will of helping nations to invest. For the latter case, potential sites belong to, or fall within the jurisdiction of, developed countries.

Comparing production costs of electricity and desalinated water can identify scenarios under which OTEC should be economical, relative to conventional technologies. Table 1 summarizes results obtained for the capital costs given in Figure 5 using a fixed rate of 10 percent, 20 year loan, and OTEC plant availability of only 80 percent. Operation and maintenance costs corresponding to approximately 1.5 percent of the capital cost are used. One scenario corresponds to small island nations, where the

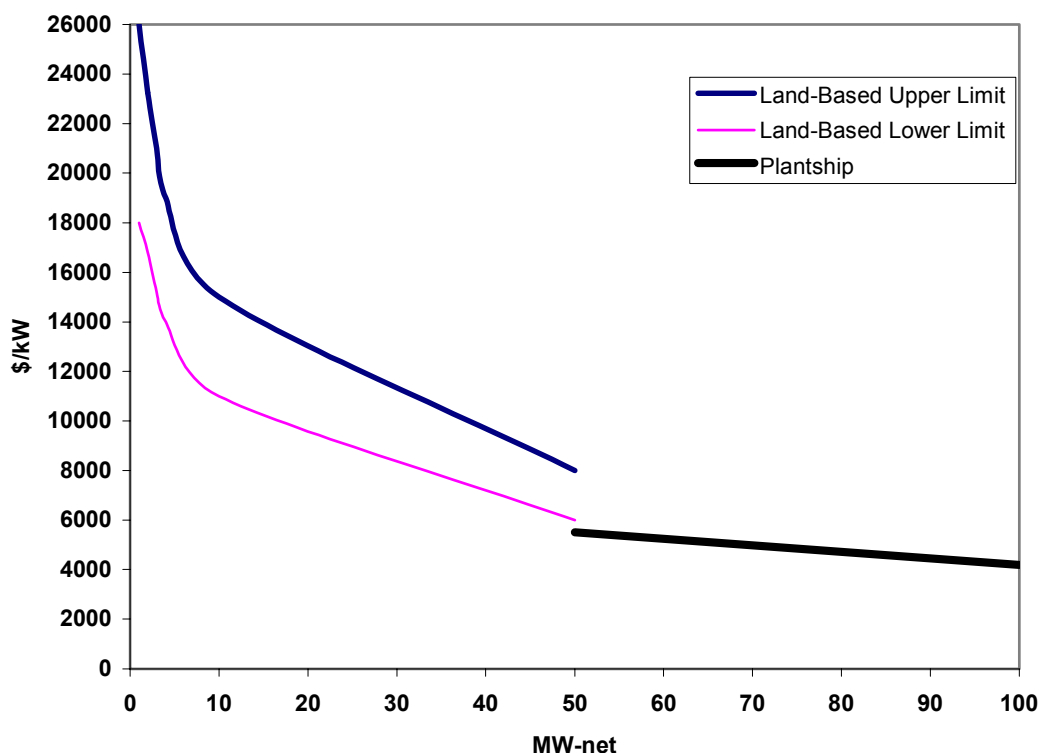


Figure 5. Capital Cost Estimates for Single-Stage OTEC Plants.

cost of diesel-generated electricity and fresh water is such that a small, 1 MW land-based OC- OTEC plant, with water production, would be cost-effective today. However, only a few sites throughout the world meet this scenario. A second scenario corresponds to conditions that are plausible in several island nations where 10 MW land-based OC-OTEC plants could produce cost competitive electricity and desalinated water. One can envision these small plants deployed in, for example, Pacific islands such that 20 years from now a total of 100 to 300 MW would be installed. A third scenario corresponds to land-based hybrid OTEC plants for the industrialized nations' market producing electricity through an ammonia cycle and desalinated water through a flash (vacuum) evaporator. This

scenario would be cost-effective in industrialized island nations with a doubling of the cost of oil fuel or with a doubling of water costs, and for plants rated at 50 MW or larger. The fourth scenario is for floating OTEC electrical plants, rated at 100 MW or larger, and housing a factory or transmitting electricity to shore via a submarine power cable. These plants could be deployed throughout the EEZ of numerous nations and could encompass a significant market. Estimates of their capital costs and resulting costs of electricity are given in Table 2.

Nominal Size, MW	TYPE	Scenario	Potential Sites
1	Land-Based OC-OTEC with 2 nd Stage for Additional Water Production.	Diesel: \$45/barrel Water: \$1.6/m ³	Present Situation in Some Small Island States.
10	Same as Above.	Fuel Oil: \$30/barrel Water: \$0.9/ m ³	U.S. Pacific Insular Areas and other Island Nations.
50	Land-Based Hybrid CC-OTEC with 2 nd Stage.	Fuel Oil: \$50/barrel Water: \$0.4/ m ³ Or Fuel Oil: \$30/barrel Water: \$0.8/ m ³	Hawaii, Puerto Rico If fuel or water cost doubles.
50	Land-Based CC-OTEC	Fuel Oil: \$40/barrel	Same as Above.
100	CC-OTEC Plantship	Fuel Oil: \$20/barrel	Numerous sites

Table 1. OTEC Potential Sites as a function of Fuel and Water Cost.

Offshore Distance, km	Capital Cost, \$/kW	COE, \$/kWh
10	4200	0.07
50	5000	0.08
100	6000	0.10
200	8100	0.13
300	10 200	0.17
400	12 300	0.22

Table 2. Cost Estimates for 100 MW CC-OTEC Plantship (COE for 10 % Fixed Rate, 20 years, Annual O&M 1% percent of Capital Cost).

12) Hydrogen Production

Several means of energy transport and delivery from plants deployed throughout the tropical oceans have been considered. OTEC energy could be transported via electrical, chemical, thermal and electrochemical carriers. The technical evaluation of non-electrical carriers leads to the consideration of hydrogen produced using electricity and desalinated water generated with OTEC technology. The product would be transported, from the OTEC plantship located at distances of 1,600 km (selected to represent the nominal distance from the tropical oceans to major industrialized centers throughout the world) to the port facility in liquid form to be primarily used as a transportation fuel. A 100 MW-net plantship can be configured to yield (by electrolysis) 1300 kg per hour of liquid hydrogen. Unfortunately, the production cost of liquid hydrogen delivered to the harbor would be equivalent to a \$250 barrel-of-crude-oil (approximately 10 times present cost). The situation is similar for the other energy carriers considered in the literature. Presently, the only energy carrier that is cost-effective for OTEC energy is the submarine power cable. This situation might be different if the external costs of energy production and consumption are accounted for.

13) Externalities

At present, the external costs of energy production and consumption are not considered in determining the charges to the user. Considering all stages of generation, from initial fuel extraction to plant decommissioning, it has been determined that no energy technology is completely environmentally benign. The additional costs associated with corrosion, health impacts, crop losses, radioactive waste, military expenditures, employment loss subsidies (tax credits and research funding for present technologies) have been estimated to range from 78 to 259 billion dollars per year. Excluding costs associated with nuclear power, the range is equivalent to adding from \$85 to \$327 to a barrel of fuel oil, increasing the present cost by a factor of 4 to 16. As a minimum, consider that the costs incurred by the military, in the USA alone, to safeguard oil supplies from overseas is at least \$15 billion corresponding to adding \$23 to a barrel of fuel — equivalent to doubling the present cost. Accounting for externalities might eventually help the development and expand the applicability of OTEC, but in the interim the future of OTEC rests in the use of plantships housing closed (or hybrid) cycle plants transmitting the electricity (and desalinated water) to land via submarine power cables (and flexible pipelines).

Conventional power plants pollute the environment more than an OTEC plant would and, as long as the sun heats the oceans, the fuel for OTEC is unlimited and free. However, it is futile to use these arguments to persuade the financial community to invest in a new technology until it has an operational record. The next step in the development of OTEC is the installation and operation of a pre-commercial plant sized such that it can be scaled to 100 MW.

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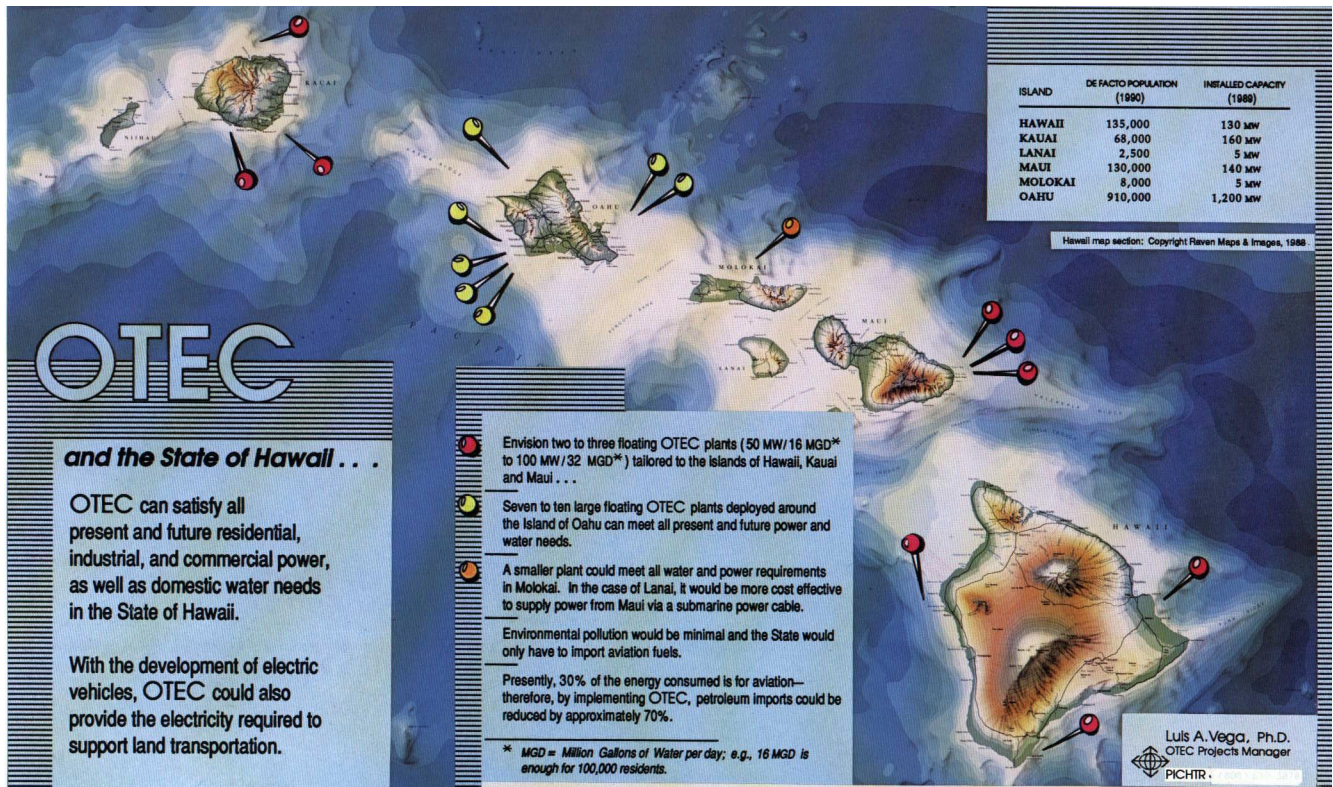
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